The value of surface-based gravity and gravity gradient measurements at the Moon's south pole with Artemis III

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Executive Summary: We recommend the deployment of gravimeters in two modalities: ***mobile*** gravimeters or gravity gradiometers (either manually operated or rover-mounted), which could be used to characterize the geologic context of a landing site; and long-lived, high-precision ***static*** gravimeters that would be used to study the deep interior and understand the origins of hazards (e.g., tidally-induced moonquakes and landslides).

Background: Gravity anomalies are produced by density variations in the Moon's interior; consequently, gravimetry and gravity gradiometry are primary tools for directly constraining the mass distribution under a landing site. As described in The Scientific Context for Exploration of the Moon [1] and its recent progress report, Advancing Science of the Moon [2], the Moon's internal structure holds the key to answering questions about its formation and evolution.

Figure 1. Field deployment of a relative gravimeter. *Illustration: Derek James*

Gravimeter and gravity gradiometer technology: Gravity can be measured using a variety of technologies that fall into three categories: *Relative gravimeters* (see Fig. 1): these instruments measure acceleration and are generally smaller than other gravity instruments. However, the readings can migrate over time due to microscopic creep in the spring mechanism or severe shocks to the instrument, so these instruments can only measure "relative" changes in gravity from one location to another, rather than the true acceleration. The Apollo 17 Traverse Gravity Experiment employed a relative gravimeter [3], although modern gravimeter designs exhibit superior performance. *Absolute gravimeters*: these instruments measure the true acceleration of gravity and are immune to drift. These are generally utilized as static instruments due to their bulk. *Gravity gradiometers*: these instruments measure the spatial rate of change of gravity acceleration in one or more directions. Gravity gradients are particularly sensitive to subtle, local density anomalies in the lunar subsurface, so they require accurate topography data.

The novelty of ground-based data: Although the NASA Gravity Recovery and Interior Laboratory (GRAIL) mission produced a global map of the Moon's gravity field [4], ground-based measurements would provide critical, complementary data. Even at its highest resolution, the GRAIL dataset is limited to spatial scales larger than several kilometers (owing to the GRAIL spacecraft altitude and separation). Consequently, ground-based measurements are required to characterize gravity anomalies at the scale of a crewed mission footprint. This increased resolution would allow for the detection and characterization of small, shallow density anomalies that would otherwise be unseen to astronauts—including lava tubes, subsurface layers, regolith thickness, buried impact geology, and the density and porosity profile of the near subsurface [5]. These techniques were successfully employed by the Mars Curiosity rover to study the sedimentary history of Gale crater [6]. Such measurements rely on a knowledge of elevation, which could be provided by stereo photographic elevation models (for example). A measurement of absolute gravity would place tight constraints on the density of topographic massifs several kilometers away [7].

A static ground-based gravimeter would also provide unique constraints on the tidal deformation of the Moon. The detected change in gravity acceleration is determined by: (1) mass redistribution inside the Moon (e.g., from elastic distortion of the mantle or motion of the Moon's inner solid core [8]); (2) the changing distance of the gravimeter from the center of the Moon due to tidal deformation of the surface; and (3) the tide-raising potential. Consequently, static ground-based gravimeters are sensitive to both the "k_{lm}" and the "h_{lm}" Love numbers. In the long-term arc of lunar exploration, tidal deformation measurements at the south pole would be the first step toward the implementation of "tidal tomography" [9], a technique that would allow us to study the Moon's deep interior to answer questions about its structure, history, and evolution [10,11,12]. Furthermore, lunar seismicity and landslides—genuine hazards for human exploration—are partly driven by tidal deformation. Thus, characterizing the Moon's tidal response from gravity can help assess risks for lunar exploration. These science objectives require microGal-level precision (see the table below), which is right at the limit of current state-of-the-art technology.

Complementarity with other geophysical instrumentation: When paired with other geophysical investigations, gravity data can enhance the overall scientific value of a mission. *Seismometers*: seismic wave velocities are determined by a combination of elastic moduli and density but seismic data alone cannot constrain density directly. Therefore, seismic data can be more uniquely interpreted with the addition of density constraints from gravity data [13], and subsurface images can constrain non-uniqueness of gravity data [14]. *Retroreflectors*: lunar laser ranging from Earth is facilitated by the deployment of passive corner-cube retroreflectors, and this yields information on the Moon's tidal deformation. However, laser ranging to the Moon's south pole would only yield the horizontal component of tidal deformation, whereas gravity measurements would indicate tidal deformation in the radial direction. Therefore, gravity and laser ranging would provide complementary, 3D measurements of the same physical process [15]. *Heat flux*: the thermal inertia and conductivity of the lunar regolith are sensitive to its density and porosity. Therefore, a gravity-derived porosity profile would aid in the interpretation of the Moon's temperature profile [16].

These combined geophysical investigations would provide more scientific value than the sum of their parts; consequently, gravimeters would be important components of a holistic geophysical field campaign on the Moon.

Science Traceability Matrix (details are provided in an appendix: arXiv:2009.03514)		
Science objective	**Relevant measurement**	**Technical requirements**
1 – Detect buried volcanic and tectonic structures	Relative gravity at multiple locations *OR*, gravity gradients in the general vicinity	Gravity with error less than 3 mGal Gravity gradients with error less than 100 Eötvös
2 – Measure porosity in the near subsurface	Relative gravity at multiple locations	Error less than 0.1 mGal, measured at elevations spanning >20 meters (topographic error <1 meter)
3 – Detect water ice in the near subsurface	Relative gravity at multiple locations	Error less than 0.1 mGal (with topographic error <20 cm)
4 – Constrain the regional density of the crust	A single measurement of absolute gravity to merge with the GRAIL dataset	Absolute gravity with error less than 20 mGal
5 – Resolve deep internal structure	Relative gravity at a fixed location *OR*, absolute gravity at a fixed location	Error less than 2 μGal over a full tidal cycle (including error arising from drift).
6 – Detect the solid inner core	Relative gravity at a fixed location *OR*, absolute gravity at a fixed location	Error less than 0.1 μGal over a full tidal cycle (including error arising from drift).

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